WAFER POLISHING CONTROL SYSTEM FOR CHEMICAL MECHANICAL PLANARIZATION MACHINES

BACKGROUND OF THE INVENTION

1. Field of Invention

The present invention relates generally to semiconductor processing equipment. More particularly, the present invention relates to a relatively compact wafer polishing apparatus which is capable of maintaining substantially uniform contact pressure on a wafer polishing area during operation.

2. Description of the Related Art

Chemical mechanical planarization apparatuses are generally used during semiconductor fabrication processes to polish wafer surfaces. As will be appreciated by those skilled in the art, chemical mechanical planarization is an abrasive process that polishes a wafer to create a smooth surface through the use of a chemical slurry and circular motions of a polishing pad and a wafer. A smooth or even surface on a wafer is critical to ensure the integrity of a semiconductor formed using the wafer, *e.g.*, to ensure that interconnects between layers of the wafer are not deformed and to ensure that desired photolithographic depths of focus are maintained.

Fig. 1a is a diagrammatic top-view representation of one conventional chemical mechanical planarization apparatus used for wafer polishing. An apparatus 102 includes a polishing pad 104 which has a significantly larger diameter than the diameter of a wafer 108. Apparatus 102 also includes a swinging arm 106 that allows polishing pad 104 to be moved relative to wafer 108, which is typically held in a wafer chuck (not shown) that, like polishing pad 104, spins while apparatus 102 is in use.

The use of polishing pad 104 that is larger than wafer 108 generally ensures that substantially even polishing of wafer 108 occurs, as a relatively even contact pressure may be readily maintained between polishing pad 104 and wafer 108. Hence, a surface

of wafer 108 may be relatively evenly polished. However, when polishing pad 104 is significantly larger than wafer 108, apparatus 102 may be inconvenient and, hence, impractical to use. For example, the overall footprint of apparatus 102 may be larger than desired, and power requirements associated with rotating polishing pad 104 relatively to wafer 108 may be higher than desired. In addition, the cost of a polishing pad 104 that is larger than a wafer 108 may be relatively high.

Some systems use a polishing pad that has a smaller diameter than a wafer being polished. Fig. 1b is a diagrammatic top-view representation of a wafer polishing apparatus which includes a polishing pad which is smaller than a wafer being polished. An apparatus 112 includes a polishing pad 114 which is arranged to polish a surface of a wafer 118. When substantially all of a polishing surface of polishing pad 114 is in contact with a surface of wafer 118, as shown, a first contact pressure may be maintained between polishing pad 114 and wafer 118. However, when at least a part of a polishing pad 114 is not in contact with a surface of wafer 118, as shown in Fig. 1c, a contact pressure between polishing pad 114 and wafer 118 is not the same as the first contact pressure which may be maintained when substantially all of a polishing surface of polishing pad 114 is in contact with wafer 118. Specifically, when polishing pad 114 has a smaller diameter than the diameter of wafer 118, the application of a constant force to polishing pad 114 does not enable a uniform contact pressure to be maintained irregardless of the position of polishing pad 114 relative to wafer 118, as the contact pressure varies depending upon how much of polishing pad 114 is in contact with wafer 118. As a result, a polishing process which involves apparatus 118 generally does not allow for a surface of wafer 118 to be evenly polished.

The inability to enable relatively even polishing of a surface of a wafer to occur unless a wafer-polishing pad has a diameter that is significantly larger than the diameter is often problematic. Often, trade-offs may have to be made between the higher costs associated with an apparatus which enables relatively even polishing of a surface and the lower costs associated with an apparatus which provides for less even polishing.

Therefore, what is needed is a relatively compact and cost-efficient apparatus which allows for relatively even polishing of a wafer surface. That is, what is desired is a chemical mechanical planarization polishing apparatus which enables a wafer-polishing pad that is not significantly larger than a wafer to provide relatively even polishing of a surface of the wafer.

SUMMARY OF THE INVENTION

The present invention relates to a chemical mechanical planarization polishing apparatus which allows a substantially uniform polishing pressure to be maintained on the wafer. According to one aspect of the present invention, a chemical mechanical planarization polishing apparatus includes a polishing pad, a wafer holder, and a force control system. The wafer holder supports a wafer to be polished using the polishing pad. The polishing pad is arranged to move relative to the wafer holder such that an area of contact between the wafer holder and the polishing pad varies. The force control system including a controller and a plurality of actuators that apply forces to the polishing pad. The controller controls the forces as the area of contact varies to substantially maintain a first polishing pressure on the wafer arranged to be supported by the wafer holder.

In one embodiment, the controller is arranged to vary the forces as the area of contact varies to substantially maintain the first polishing pressure on the wafer arranged to be supported by the wafer holder. In another embodiment, the controller determines the forces based upon a position associated with the polishing pad, the first polishing pressure, an air pressure load on the polishing pad, and a distance between a center of the polishing pad and a center of gravity associated with the chemical mechanical planarization apparatus.

A chemical mechanical planarization polishing apparatus which includes a force control system that allows the magnitude of forces applied on a polishing pad to be adjusted as needed enables a substantially uniform polishing pressure to be maintained on a wafer that is being polished using the apparatus. By allowing a desired polishing pressure to be maintained regardless of how large a contact area between the polishing pad and the wafer is, *i.e.*, by adjusting forces applied by actuators of the force control system based upon the size of a contact area between the polishing surface of the polishing pad and the polishing surface of the wafer, the likelihood that the integrity of the polished wafer is compromised during the polishing process may be reduced.

According to another aspect of the present invention, a method for planarizing a surface of a wafer using an apparatus which includes a force system with a plurality of actuators, a polishing pad, and a chuck arranged to support the wafer substantially in contact with the polishing pad involves polishing the wafer using the polishing pad. Polishing the wafer using the polishing pad includes rotating the wafer while the wafer is in contact with the polishing pad. The method also includes determining a current area of contact between the polishing pad and the wafer, and adjusting the forces applied by each of the plurality of actuators to substantially maintain a first polishing pressure on the wafer. The magnitudes of the forces are adjusted based upon the current area of contact.

In one embodiment, the method also includes determining the forces to be applied by each of the plurality of actuators to substantially maintain the first polishing pressure on the wafer. Determining the forces includes determining a current position associated with the polishing pad, identifying the first polishing pressure, identifying an air pressure load on the polishing pad, and determining a current distance between a center of the polishing pad and a center of gravity associated with the chemical mechanical planarization apparatus.

These and other advantages of the present invention will become apparent upon reading the following detailed descriptions and studying the various figures of the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention may best be understood by reference to the following description taken in conjunction with the accompanying drawings in which:

Fig. 1a is a diagrammatic top-view representation of one conventional chemical mechanical planarization apparatus used for wafer polishing.

Fig. 1b is a diagrammatic top-view representation of a wafer polishing apparatus which includes a polishing pad which is smaller than a wafer being polished.

Fig. 1c is a diagrammatic top-view representation of a wafer polishing apparatus which includes a polishing pad which is smaller than a wafer being polished and is not completely in contact with the wafer.

Fig. 2 is a diagrammatic top-view representation of a chemical mechanical planarization polishing apparatus in accordance with an embodiment of the present invention.

Fig. 3 is a block diagram representation of a polishing apparatus with a non-contact force system in accordance with an embodiment of the present invention.

Fig. 4 is a diagrammatic representation of an orientation of actuators of a force system in accordance with an embodiment of the present invention.

Fig. 5 is a block diagram representation of a wafer polishing control system which is suitable for controlling a wafer polishing apparatus in accordance with an embodiment of the present invention.

Figs. 6a and 6b are a process flow diagram which illustrates a method of performing chemical mechanical planarization polishing on a wafer in accordance with an embodiment of the present invention.

Fig. 7 is a diagrammatic representation of a wafer polishing force distribution in accordance with an embodiment of the present invention.

Fig. 8 is a signal flow chart for a force control system module in accordance with an embodiment of the present invention.

Fig. 9 is a diagrammatic representation of a photolithography apparatus in accordance with an embodiment of the present invention.

Fig. 10 is a process flow diagram which illustrates the steps associated with fabricating a semiconductor device in accordance with an embodiment of the present invention.

Fig. 11 is a process flow diagram which illustrates the steps associated with processing a wafer, *i.e.*, step 1304 of Fig. 10, in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION OF THE EMBODIMENTS

The careful control of chemical mechanical planarization machines used for wafer polishing is crucial in ensuring that the integrity of a wafer polished using a chemical mechanical planarization machine is not significantly compromised. When a chemical mechanical planarization machine includes a polishing pad which has a smaller diameter than a wafer that is to be polished, when the polishing pressure applied by the polishing pad on the wafer is not accurately controlled, the polished surface of the wafer may be relatively uneven, which often compromises the integrity of semiconductor devices formed using the wafer.

A force control system which includes a plurality of actuators that are arranged to apply different magnitudes of forces to sections of a polishing pad may be included as a part of a chemical mechanical planarization apparatus. Such a force control system allows the magnitude of forces applied on a polishing pad to be adjusted as needed to maintain a substantially uniform polishing pressure. The ability to adjust forces applied to different sections or areas of a polishing pad enables a substantially uniform polishing pressure to be effectively maintained irregardless of whether substantially all of the

polishing surface of the polishing pad or only part of the polishing surface of the polishing pad are in contact with the polishing surface of a wafer. That is, the polishing pressure may be maintained at a desired level by adjusting forces applied by actuators of the force control system based upon the size of a contact area between the polishing surface of the polishing pad and the polishing surface of the wafer.

Fig. 2 is a diagrammatic top-view representation of a chemical mechanical planarization polishing apparatus which includes a force control system in accordance with an embodiment of the present invention. A polishing apparatus 200 includes a polishing pad 204 and a wafer chuck 214 which holds a wafer 208 such that wafer 208 may come into contact with polishing pad 204 during a wafer polishing or planarization process. Apparatus 200 also includes an arm 218 which is coupled to an air pressure load system 226 and a force control system or a force system 224, *e.g.*, an electromagnetic force system, that is arranged to control the amount of force applied to polishing pad 204 based on instructions provided by a controller 222. The forces applied to polishing pad 204 using force system 224 may be suction forces which allows portions of polishing pad 204 to effectively be pulled up.

During wafer polishing, polishing pad 204 is moving and wafer 208 is spinning or rotating, and polishing pad 204 contacts wafer 208 with a desired polishing pressure that is provided by a head base weight associated with a polishing head (not shown) which supports polishing pad 204 and air pressure load system 226. Force system 224 is arranged to substantially cooperate with air-pressure load system 226 to balance the polishing head (not shown) and to maintain a substantially uniform contact pressure on a polishing surface of wafer 208. In one embodiment, forces associated with actuators in force system 224 are controlled to effectively compensate for the air pressure load provided by air pressure load system 226.

In general, actuators which are a part of force system 224 may be substantially any suitable actuators. Suitable actuators include, but are not limited to, EI-core

actuators, CI-core actuators, and various other electromagnetic actuators. Actuators which are a part of force system 224 may be individually controlled to effectively dynamically compensate for an air load such that relatively even polishing may occur on a surface of wafer 208 irregardless of how polishing pad 204 is positioned relative to wafer 208. By way of example, force system 224 may be controlled by controller 222 such that a surface of wafer 208 may be evenly polished whether a part of a polishing surface of polishing pad 204 is not in contact with the surface of wafer 208 or whether substantially all of the polishing surface of polishing pad 204 is in contact with the surface of wafer 208.

Force system 224 is generally a non-contact force system. By way of example, when force system 224 includes actuators that are EI-core actuators, E-cores of the actuators may be coupled to force system 224 while I-cores of the actuators are coupled to polishing pad 204 or an arrangement which supports polishing pad 204. Force system 224 operates by providing an attraction force to a polishing pad arrangement which includes polishing pad 204, *e.g.*, such that an E-core attracts an I-core. The attraction force pulls up on, *e.g.*, effectively applies suction to, polishing pad 204 as appropriate to compensate for the air load. Fig. 3 is a block diagram representation of a polishing apparatus with a non-contact force system in accordance with an embodiment of the present invention. A polishing apparatus 300 includes a rotating wafer 308 which is arranged substantially beneath a moving polishing pad arrangement 305 which is suitable for polishing, *e.g.*, abrading, a top surface of the rotating wafer. A fixed, non-contact force system 324 is arranged over rotating polishing pad arrangement 305 such that force system 324 may apply magnetic forces that effectively pull up on portions of a polishing pad of rotating polishing pad arrangement 305. By pulling up portions of the polishing pad, the overall polishing pressure associated with polishing a surface of rotating wafer 308 may be maintained at a constant level such that even polishing may occur irregardless of whether all of or only a portion of a polishing surface of a rotating polishing pad comes into contact with rotating wafer 308.

When force system 324 includes E-cores of EI-core actuators, and rotating polishing pad arrangement 305 includes I-cores of the EI-core actuators, gap distances between each E-core and each I-core may be changed to substantially directly affect the amount of attraction force effectively applied to portions of a polishing pad. Hence, E-cores of force system 324 may be used to control the overall polishing force associated with rotating polishing pad arrangement 305. As will be appreciated by those skilled in the art, varying the current provided to a coil of an E-core allows the attraction force between the E-core and a corresponding I-core to be changed or otherwise controlled. In one embodiment, multiple E-cores may essentially be associated with a single I-core of a ring-shaped configuration, as described in co-pending U.S. Patent Application No. 10/430,598, filed May 5, 2003, which is incorporated herein by its entirety.

A force system such as force system 324 may include any number of actuators. For example, a force system may include three actuators that are positioned such that a first actuator is located substantially over the inner part of a polishing pad which is the closest point to the wafer center, and second and third actuators are located substantially opposite from the first actuator, *i.e.*, at slight offsets from approximately 180 degrees away from the first actuator. As shown in Fig. 4, a first actuator 424a of a force system 422 may be located substantially opposite, *i.e.*, 180 degrees from, a center point 430 between a second actuator 424b and a third actuator 424c. Second actuator 424b and third actuator 424c are generally positioned at a slight offset from a centerline 434 of force system 422 which passes through first actuator 424a.

In the described embodiment, actuators 424b, 424c are effectively controlled together to apply sufficient force to pull up an edge of a polishing pad when the polishing surface associated with the edge of the polishing pad is not in contact with a wafer being polished. It should be appreciated, however, that actuators 424b, 424c may also be controlled separately. In addition, the location of actuators 424b, 424c may vary.

The amount of force applied using actuators 424 is dependent upon the overall location of a polishing pad which is subjected to the force applied using actuators 424. Hence, given a desired polishing pressure, a controller, *e.g.*, controller 222 of Fig. 2, may determine forces to be applied using actuators 424 as a function of a location of the polishing pad.

Fig. 5 is a block diagram representation of a wafer polishing control system which is suitable for controlling a wafer polishing apparatus such as polishing apparatus 200 of Fig. 2 in accordance with an embodiment of the present invention. A chemical mechanical planarization host computer 502, which may be substantially any suitable computing system which includes a processor for processing command instructions, is arranged to provide arm movement control 506 for a swinging arm. Controlling arm movement allows a current polishing pad position to be determined, and provided to an electromagnetic force control system 510 or, more generally, a force system which is used to effectively control a polishing pressure between the polishing pad and a wafer being polished. The amount of force generated by each actuator included in electromagnetic force control system 510 is dependent upon a current polishing pad position.

In addition to a current pad position, electromagnetic force control system 510 also receives information relating to a fixed air load force and a desired polishing pressure from host computer 502. During wafer polishing, the rotating polishing pad touches the surface of the wafer to be polished at a desired polishing pressure, which may be determined by a head base weight and air air-pressure load system. Electromagnetic force control system 510 is arranged to substantially compensate for an overloaded air-pressure force to balance the polishing head which supports the polishing pad, and to maintain substantially uniform contact pressure on the polishing surface of the wafer.

Host computer 502 is also arranged to provide an air pressure load control system 514 with instructions, and to provide instructions to a pad and chuck rotation controller

518. That is, host computer 502 allows an air-pressure load to be controlled, and also allows rotation of both a polishing pad and a wafer chuck which supports a wafer to be controlled.

With reference to Figs. 6a and 6b, the steps associated with one method of performing chemical mechanical planarization polishing on a wafer will be described in accordance with an embodiment of the present invention. A process 600 of performing chemical mechanical planarization polishing begins at step 604 in which a wafer that is to be polished is moved to, or otherwise positioned in, a wafer chuck of a polishing apparatus. Then, in step 608, various parameters associated with a polishing process are set. By way of example, a polishing pressure, a polishing time, a polishing pad rotation speed, a wafer chuck rotation speed, and an arm moving trajectory may be set.

Once parameters associated with the polishing process are set, an air-pressure load is set in step 612. After a predetermined amount of time, during which air may effectively be pumped to the polishing pad, a determination is then made in step 616 as to whether an air-load set point has been reached. If it is determined that the air-load set point has not been reached, then process flow returns to step 612 in which an air-pressure load is set.

Alternatively, if it is determined in step 616 that the air-load set point has been reached, then process flow proceeds to step 620 in which the polishing pad and the wafer chuck begin spinning. In step 624, the polishing head or, more specifically, the polishing pad, is effectively lowered to come into contact with the wafer supported on the wafer chuck. After lowering the polishing pad, actuators of a force system are turned on in step 628. In the described embodiment, the actuators are electromagnetic actuators, and turning on the actuators may include providing current to coils associated with the electromagnetic actuators.

Upon turning on the actuators, the actuators begin to ramp up to set forces in step 632 which are appropriate to achieve the polishing pressure set in step 608. A determination is made in step 636 regarding whether the set forces have been reached. It should be appreciated that such a determination may be made after a predetermined amount of time has elapsed. If it is determined that the set forces have not been reached, process flow returns to step 632 in which the actuators continue to ramp up to set forces. Alternatively, if it is determined that set forces have been reached, the arm moves, and polishing occurs while actuator forces change 640. As previously mentioned, the actuator forces change to provide a uniform polishing pressure irregardless of whether substantially all of a polishing surface of a polishing pad is in contact with a wafer, or only a portion of the polishing surface of the polishing pad is in contact with the wafer.

In step 644, it is determined if there is an unbalanced force associated with the polishing apparatus. If it is determined that there is an unbalanced force, then the polishing process is aborted. If it is determined that there is no unbalanced force, a determination is made in step 648 as to whether the polishing time set in step 608 has been reached. When it is determined that the polishing time has not been reached, process flow returns to step 640 in which polishing continues to occur while actuator forces change as appropriate.

If the determination in step 648 is that the polishing time has been reached, then the actuators are turned off in step 652, and the polishing head is lifted in step 656. Once the polishing head is lifted, the spinning of the polishing pad and the wafer chuck is stopped in step 660. Finally, the wafer is removed from the chuck in step 664, and the process of performing chemical mechanical planarization polishing is completed.

In order to determine actuator output forces needed to maintain a desired polishing pressure irregardless of a polishing pad location, the force distribution associated with a polishing apparatus that includes a force system with actuators may be studied. A command force vector F, which includes output forces for actuators, may be

determined to be a function of an air pressure load and base weight, a resistant force from a wafer, and the contact area between a polishing pad and the wafer.

Fig. 7 is a diagrammatic representation of a wafer polishing force distribution in accordance with an embodiment of the present invention. A polishing pad 704 and a wafer 708 have a contact area 'A' 746 which is a function of a position of a center of pressure 722 of polishing pad 704 relative to a center of wafer 748. That is, contact area 'A' 746 is a function of a distance 'x' 750 between center of pressure 722 and center of wafer 748, *i.e.*, contact area 'A' 746 is effectively contact area 'A(x)' 746. It should be appreciated that contact area 'A(x)' 746 may be calculated such that for every distance 'x' 750, or pad position, the corresponding contact area 'A(x)' 746 is known before a polishing apparatus which includes polishing pad 704 and wafer 708 is put into use.

An air load 'L' 760 is effectively applied to polishing pad 704 through center of pressure 722. Air load 'L' 760 is an air pressure load, which is a passive load. Actuators 718 which are part of a force system apply forces 'F_2' 758 at a distance 'r_2' 764 from center of pressure 722. An actuator 714 applies a force 'F_1' 754 at a distance 'r_1' 762 from center of pressure 722. Force 'F_1' 754 and forces 'F_2' 758 are arranged to enable a substantially uniform or desired polishing contact pressure 'P' to be maintained on wafer 708. Hence, force 'F_1' 754 and forces 'F_2' 758 are adjusted depending upon contact area 'A(x)' 746. In the described embodiment, actuator 718a and actuator 718b are arranged to provide forces 'F_2' 758 of substantially the same magnitude and are, hence, effectively controlled together.

A resistant force 'R' 774 is a function of distance 'x' 750, and is a resistant force from wafer 708. A gravity center distance 'g' 770 varies depending on distance 'x' 750, and expresses a distance between a point where resistant force 'R' 774 acts and center of pressure 722. That is, gravity center distance 'g' 770 at a point in time is a distance between center of pressure 722 and a center of gravity associated with pad 704 and wafer 708 at the point in time. Gravity center distance 'g' 770 may be calculated in real-time as

a function of distance 'x' 750, *i.e.*, while a polishing apparatus which includes polishing pad 704 is in use, using geometric relationships, or may be determined while the polishing apparatus is in use through the use of a pre-calculated look-up table which lists gravity center distances relative to pad positions.

Resistant force 'R' 774 is generally dependent upon a desired polishing pressure 'P' and contact area 'A' 746, as well as distance 'x' 750. Hence, resistant force 'R' 774 may be expressed as follows:

$$R(x) = P \cdot A(x)$$

As previously mentioned, contact area 'A' 746 may be predetermined, or calculated prior to using polishing pad 704, as a function of pad position or distance 'x' 750. It should be appreciated by those skilled in the art that geometric relationships may be used to calculate contact area 'A' 746 as a function of distance 'x' 750. Polishing pressure 'P' is a desired polishing pressure which is to be maintained while wafer 708 is being polished using polishing pad 704.

Balancing forces and moments on pad 704 and wafer 770 yields the following equations:

$$F_1 + 2 \cdot F_2 + R(x) = L$$
$$F_1 \cdot r_1 + R(x) \cdot g(x) = 2 \cdot F_2 \cdot r_2$$

Rewritten in matrix form, the above equations may be expressed as:

$$\begin{bmatrix} 1 & 2 \\ r_1 & -2r_2 \end{bmatrix} \begin{bmatrix} F_1 \\ F_2 \end{bmatrix} = \begin{bmatrix} L - R(x) \\ -R(x) \cdot g(x) \end{bmatrix}$$

Substituting for resistant force 'R' 774 yields:

$$\begin{bmatrix} 1 & 2 \\ r_1 & -2r_2 \end{bmatrix} \begin{bmatrix} F_1 \\ F_2 \end{bmatrix} = \begin{bmatrix} L - P \cdot A(x) \\ -P \cdot A(x) \cdot g(x) \end{bmatrix}$$

A force command vector $\hat{F}$ which expresses desired forces F_1 754 and F_2 758, to be produced by actuators 714, 718, respectively, may be given as:

$$\hat{F} = \begin{bmatrix} F_1 \\ F_2 \end{bmatrix} = \begin{bmatrix} 1 & 2 \\ r_1 & -2r_2 \end{bmatrix}^{-1} \cdot \begin{bmatrix} L - P \cdot A(x) \\ -P \cdot A(x) \cdot g(x) \end{bmatrix}$$

Since distance 'r_1' 762, distance 'r_2' 764, air-pressure load force and base weight 'L' 760, and desired pressure 'P' are known, *e.g.*, given by a user or operator of an overall chemical mechanical planarization polishing apparatus, force command vector $\hat{F}$ may be determined given distance 'x' 750, as contact area 'A' 746 and gravity center distance 'g' 770 are effectively known if distance 'x' 750 is given.

Referring next to Fig. 8, a signal flow chart for a force control system module will be described in accordance with an embodiment of the present invention. Within a force control system 800, a pad position 850, which is a function of time since a polishing pad moves relative to a wafer during polishing, is provided to geometric equations 890. Through the use of geometric equations or relationships 890, pad position 850 may be used to determine a contact area and a gravity center distance 872 as functions of pad position 850 and, hence, time. Contact area and gravity center distance 872 are then provided to a transform matrix 892, along with an air-pressure load 860 and a desired polishing pressure 866, to enable a force command vector $\hat{F}$ 856, or desired forces, to be determined. That is, given desired polishing pressure 866, preset air-pressure load 860, pad position 850 or a pad position trajectory from an arm encoder signal, force command vector $\hat{F}$ 856 may be determined for all actuators associated with force control system 800. In the described embodiment, force control system 800 has three associated electromagnetic actuators, so force command vector $\hat{F}$ 856 may include three forces. When at least two of the electromagnetic actuators are controlled together, then force command vector $\hat{F}$ 856 may include a force to be produced by a first electromagnetic actuator and a force to be produced by each of the electromagnetic actuators that are controlled together.

Force command vector $\hat{F}$ 856 is provided as input to a feedback control system 894 which, through the use of sensors, as for example load cell force sensors, provides an

actual force output 896 for each actuator that is sent as a feedback signal to feedback control system 894. It should be appreciated that actual force output 896 for each actuator is the force generated by each actuator, and is ideally substantially equal to forces specified in force command vector $\hat{F}$ 856.

In one embodiment, when force control system 800 reads encoder counts and converts the encoder counts to pad position 850 at substantially every servo sampling time, force control system 800 may update a desired compensation force trajectory, i.e., by updating force command vector $\hat{F}$ 856. The new computed compensation force trajectory may be provided to each actuator associated with force control system 800 in order for each actuator to generate a substantially desired actual output force 896.

Generally, the configuration of feedback control system 894 may vary widely. Typically, feedback control system 894 includes an adaptive gain adjustment servomechanism which uses a real-time force gain estimate scheme and an extra adaptive gain adjustment block in a servo loop. One suitable feedback control system is described in co-pending U.S. Patent Application No. 10/430,598, which has been incorporated by reference in its entirety.

With reference to Fig. 9, a photolithography apparatus which be used to as a part of an overall semiconductor fabrication apparatus that also includes a chemical mechanical planarization polishing apparatus. A photolithography apparatus (exposure apparatus) 40 includes a wafer positioning stage 52 that may be driven by a planar motor (not shown), as well as a wafer table 51 that is magnetically coupled to wafer positioning stage 52 by utilizing an EI-core actuator, *e.g.*, an EI-core actuator with a top coil and a bottom coil which are substantially independently controlled. The planar motor which drives wafer positioning stage 52 generally uses an electromagnetic force generated by magnets and corresponding armature coils arranged in two dimensions. A wafer 64 is held in place on a wafer holder or chuck 74 which is coupled to wafer table 51. Wafer positioning stage 52 is arranged to move in multiple degrees of freedom, *e.g.*, in up to six

degrees of freedom, under the control of a control unit 60 and a system controller 62. The movement of wafer positioning stage 52 allows wafer 64 to be positioned at a desired position and orientation relative to a projection optical system 46.

Wafer table 51 may be levitated in a z-direction 10b by any number of voice coil motors (not shown), *e.g.*, three voice coil motors. In one described embodiment, at least three magnetic bearings (not shown) couple and move wafer table 51 along a y-axis 10a. The motor array of wafer positioning stage 52 is typically supported by a base 70. Base 70 is supported to a ground via isolators 54. Reaction forces generated by motion of wafer stage 52 may be mechanically released to a ground surface through a frame 66. One suitable frame 66 is described in JP Hei 8-166475 and U.S. Patent No. 5,528,118, which are each herein incorporated by reference in their entireties.

An illumination system 42 is supported by a frame 72. Frame 72 is supported to the ground via isolators 54. Illumination system 42 includes an illumination source, which may provide a beam of EUV light that may be reflected off of a reticle. In one embodiment, illumination system 42 may be arranged to project a radiant energy, *e.g.*, light, through a mask pattern on a reticle 68 that is supported by and scanned using a reticle stage 44 which includes a coarse stage and a fine stage. It should be appreciated that for such an embodiment, photolithography apparatus 40 may be a part of a system other than an EUV lithography system. In general, a stage with isolated actuators may be used as a part of substantially any suitable photolithography apparatus, and is not limited to being used as a part of an EUV lithography system. The radiant energy is focused through projection optical system 46, which is supported on a projection optics frame 50 and may be supported the ground through isolators 54. Suitable isolators 54 include those described in JP Hei 8-330224 and U.S. Patent No. 5,874,820, which are each incorporated herein by reference in their entireties.

A first interferometer 56 is supported on projection optics frame 50, and functions to detect the position of wafer table 51. Interferometer 56 outputs information on the

position of wafer table 51 to system controller 62. In one embodiment, wafer table 51 has a force damper which reduces vibrations associated with wafer table 51 such that interferometer 56 may accurately detect the position of wafer table 51. A second interferometer 58 is supported on projection optical system 46, and detects the position of reticle stage 44 which supports a reticle 68. Interferometer 58 also outputs position information to system controller 62.

It should be appreciated that there are a number of different types of photolithographic apparatuses or devices. For example, photolithography apparatus 40, or an exposure apparatus, may be used as a scanning type photolithography system which exposes the pattern from reticle 68 onto wafer 64 with reticle 68 and wafer 64 moving substantially synchronously. In a scanning type lithographic device, reticle 68 is moved perpendicularly with respect to an optical axis of a lens assembly (projection optical system 46) or illumination system 42 by reticle stage 44. Wafer 64 is moved perpendicularly to the optical axis of projection optical system 46 by a wafer stage 52. Scanning of reticle 68 and wafer 64 generally occurs while reticle 68 and wafer 64 are moving substantially synchronously.

Alternatively, photolithography apparatus or exposure apparatus 40 may be a step-and-repeat type photolithography system that exposes reticle 68 while reticle 68 and wafer 64 are stationary, *i.e.*, at a substantially constant velocity of approximately zero meters per second. In one step and repeat process, wafer 64 is in a substantially constant position relative to reticle 68 and projection optical system 46 during the exposure of an individual field. Subsequently, between consecutive exposure steps, wafer 64 is consecutively moved by wafer positioning stage 52 perpendicularly to the optical axis of projection optical system 46 and reticle 68 for exposure. Following this process, the images on reticle 68 may be sequentially exposed onto the fields of wafer 64 so that the next field of semiconductor wafer 64 is brought into position relative to illumination system 42, reticle 68, and projection optical system 46.

It should be understood that the use of photolithography apparatus or exposure apparatus 40, as described above, is not limited to being used in a photolithography system for semiconductor manufacturing. For example, photolithography apparatus 40 may be used as a part of a liquid crystal display (LCD) photolithography system that exposes an LCD device pattern onto a rectangular glass plate or a photolithography system for manufacturing a thin film magnetic head.

The illumination source of illumination system 42 may be g-line (436 nanometers (nm)), i-line (365 nm), a KrF excimer laser (248 nm), an ArF excimer laser (193 nm), and an F_2-type laser (157 nm). Alternatively, illumination system 42 may also use charged particle beams such as x-ray and electron beams. For instance, in the case where an electron beam is used, thermionic emission type lanthanum hexaboride (LaB_6) or tantalum (Ta) may be used as an electron gun. Furthermore, in the case where an electron beam is used, the structure may be such that either a mask is used or a pattern may be directly formed on a substrate without the use of a mask.

With respect to projection optical system 46, when far ultra-violet rays such as an excimer laser is used, glass materials such as quartz and fluorite that transmit far ultra-violet rays is preferably used. When either an F_2-type laser or an x-ray is used, projection optical system 46 may be either catadioptric or refractive (a reticle may be of a corresponding reflective type), and when an electron beam is used, electron optics may comprise electron lenses and deflectors. As will be appreciated by those skilled in the art, the optical path for the electron beams is generally in a vacuum.

In addition, with an exposure device that employs vacuum ultra-violet (VUV) radiation of a wavelength that is approximately 200 nm or lower, use of a catadioptric type optical system may be considered. Examples of a catadioptric type of optical system include, but are not limited to, those described in Japan Patent Application Disclosure No. 8-171054 published in the Official gazette for Laid-Open Patent Applications and its counterpart U.S. Patent No. 5,668,672, as well as in Japan Patent Application Disclosure

No. 10-20195 and its counterpart U.S. Patent No. 5,835,275, which are all incorporated herein by reference in their entireties. In these examples, the reflecting optical device may be a catadioptric optical system incorporating a beam splitter and a concave mirror. Japan Patent Application Disclosure (Hei) No. 8-334695 published in the Official gazette for Laid-Open Patent Applications and its counterpart U.S. Patent No. 5,689,377, as well as Japan Patent Application Disclosure No. 10-3039 and its counterpart U.S. Patent No. 5,892,117, which are all incorporated herein by reference in their entireties. These examples describe a reflecting-refracting type of optical system that incorporates a concave mirror, but without a beam splitter, and may also be suitable for use with the present invention.

Further, in photolithography systems, when linear motors (see U.S. Patent Nos. 5,623,853 or 5,528,118, which are each incorporated herein by reference in their entireties) are used in a wafer stage or a reticle stage, the linear motors may be either an air levitation type that employs air bearings or a magnetic levitation type that uses Lorentz forces or reactance forces. Additionally, the stage may also move along a guide, or may be a guideless type stage which uses no guide.

Alternatively, a wafer stage or a reticle stage may be driven by a planar motor which drives a stage through the use of electromagnetic forces generated by a magnet unit that has magnets arranged in two dimensions and an armature coil unit that has coil in facing positions in two dimensions. With this type of drive system, one of the magnet unit or the armature coil unit is connected to the stage, while the other is mounted on the moving plane side of the stage.

Movement of the stages as described above generates reaction forces which may affect performance of an overall photolithography system. Reaction forces generated by the wafer (substrate) stage motion may be mechanically released to the floor or ground by use of a frame member as described above, as well as in U.S. Patent No. 5,528,118 and published Japanese Patent Application Disclosure No. 8-166475. Additionally, reaction

forces generated by the reticle (mask) stage motion may be mechanically released to the floor (ground) by use of a frame member as described in U.S. Patent No. 5,874,820 and published Japanese Patent Application Disclosure No. 8-330224, which are each incorporated herein by reference in their entireties.

Isolaters such as isolators 54 may generally be associated with an active vibration isolation system (AVIS). An AVIS generally controls vibrations associated with forces 112, *i.e.*, vibrational forces, which are experienced by a stage assembly or, more generally, by a photolithography machine such as photolithography apparatus 40 which includes a stage assembly.

A photolithography system according to the above-described embodiments, *e.g.*, a photolithography apparatus which may include one or more dual force actuators, may be built by assembling various subsystems in such a manner that prescribed mechanical accuracy, electrical accuracy, and optical accuracy are maintained. In order to maintain the various accuracies, prior to and following assembly, substantially every optical system may be adjusted to achieve its optical accuracy. Similarly, substantially every mechanical system and substantially every electrical system may be adjusted to achieve their respective desired mechanical and electrical accuracies. The process of assembling each subsystem into a photolithography system includes, but is not limited to, developing mechanical interfaces, electrical circuit wiring connections, and air pressure plumbing connections between each subsystem. There is also a process where each subsystem is assembled prior to assembling a photolithography system from the various subsystems. Once a photolithography system is assembled using the various subsystems, an overall adjustment is generally performed to ensure that substantially every desired accuracy is maintained within the overall photolithography system. Additionally, it may be desirable to manufacture an exposure system in a clean room where the temperature and humidity are controlled.

Further, semiconductor devices may be fabricated using systems described above, as will be discussed with reference to Fig. 10. The process begins at step 1301 in which the function and performance characteristics of a semiconductor device are designed or otherwise determined. Next, in step 1302, a reticle (mask) in which has a pattern is designed based upon the design of the semiconductor device. It should be appreciated that in a parallel step 1303, a wafer is made from a silicon material. Making a wafer may include subjecting the wafer to a chemical mechanical planarization process that allows a surface of the wafer to be polished. The mask pattern designed in step 1302 is exposed onto the wafer fabricated in step 1303 in step 1304 by a photolithography system. One process of exposing a mask pattern onto a wafer will be described below with respect to Fig. 11. In step 1305, the semiconductor device is assembled. The assembly of the semiconductor device generally includes, but is not limited to, wafer dicing processes, bonding processes, and packaging processes. Finally, the completed device is inspected in step 1306.

Fig. 11 is a process flow diagram which illustrates the steps associated with wafer processing in the case of fabricating semiconductor devices in accordance with an embodiment of the present invention. In step 1311, the surface of a wafer is oxidized. Then, in step 1312 which is a chemical vapor deposition (CVD) step, an insulation film may be formed on the wafer surface. Once the insulation film is formed, in step 1313, electrodes are formed on the wafer by vapor deposition. Then, ions may be implanted in the wafer using substantially any suitable method in step 1314. As will be appreciated by those skilled in the art, steps 1311-1314 are generally considered to be preprocessing steps for wafers during wafer processing. Further, it should be understood that selections made in each step, *e.g.*, the concentration of various chemicals to use in forming an insulation film in step 1312, may be made based upon processing requirements.

At each stage of wafer processing, when preprocessing steps have been completed, post-processing steps may be implemented. During post-processing, initially, in step 1315, photoresist is applied to a wafer. Then, in step 1316, an exposure device

may be used to transfer the circuit pattern of a reticle to a wafer. Transferring the circuit pattern of the reticle of the wafer generally includes scanning a reticle scanning stage which may, in one embodiment, include a force damper to dampen vibrations.

After the circuit pattern on a reticle is transferred to a wafer, the exposed wafer is developed in step 1317. Once the exposed wafer is developed, parts other than residual photoresist, *e.g.*, the exposed material surface, may be removed by etching. Finally, in step 1319, any unnecessary photoresist that remains after etching may be removed. As will be appreciated by those skilled in the art, multiple circuit patterns may be formed through the repetition of the preprocessing and post-processing steps.

Although only a few embodiments of the present invention have been described, it should be understood that the present invention may be embodied in many other specific forms without departing from the spirit or the scope of the present invention. By way of example, a force control system has generally been described as having three actuators, two of which are arranged to provide substantially the same force when the force control system is in use. In general, however, a force control system may include any number of actuators. Additionally, the actuators of a force control system may all be substantially individually controlled, and the spacing of the actuators may also vary.

Geometric equations or relationships used to determine the size of a contact area between a polishing pad and a wafer as a function of a location of the center of pressure of the polishing pad may vary. That is, any suitable geometric relationships may be used to determine the contact area.

Electromagnetic actuators have generally been described as being suitable for use as actuators in a force control system. Electromagnetic actuators may include, but are not limited to, EI-core and CI-core actuators. It should be appreciated, however, that substantially any suitable actuators, electromagnetic or otherwise, may be used as a part of a force control system for a chemical mechanical planarization polishing apparatus.

The steps associated with a wafer polishing operation may vary depending, for example, on the overall requirements of a semiconductor fabrication process. Steps may be added, removed, reordered, and changed without departing from the spirit or the scope of the present invention. Therefore, the present examples are to be considered as illustrative and not restrictive, and the invention is not to be limited to the details given herein, but may be modified within the scope of the appended claims.